Chapter 19

QUANTUM PHYSICS

speed of light in free space	c	=	3.00×10^{8} m s^{-1}
elementary charge	e	=	1.60×10^{-19} C
the Planck constant	h	=	6.63×10^{-34} Js
unified atomic mass constant	u	=	1.66×10^{-27} kg
rest mass of electron	m_e	=	9.11×10^{-31} kg
rest mass of proton	m_p	=	1.67×10^{-27} kg

Self-Attempt Questions

Photoelectric Effect

1 What provides evidence for the particulate nature of electromagnetic radiation?

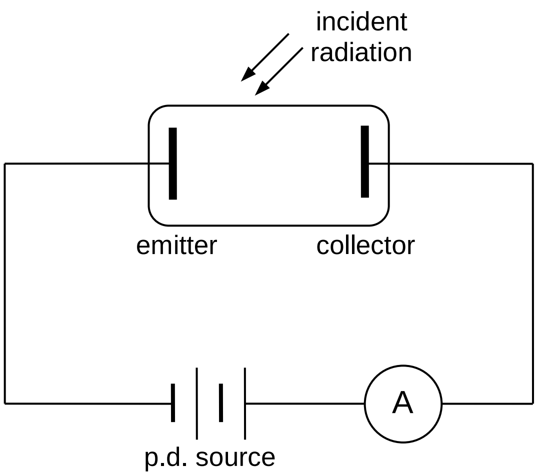
A Electrons can be diffracted by a carbon film.

B Light can be diffracted by an obstacle.

C Light from two coherent sources can produce an interference pattern.

D Photoelectric emission occurs only for incident frequencies above a minimum value.

2 The figure below shows a setup used to investigate the photoelectric effect.



When radiation of wavelength 225 nm is incident on the emitter, photoelectrons are emitted and a photocurrent is registered by the ammeter.

Which of the following statements is true?

A If the polarity of the p.d. source is switched around, photoelectrons will not be emitted anymore.

B If radiation of a shorter wavelength is used, the ammeter will register a higher photocurrent.

C If radiation of a longer wavelength is used, the ammeter will register a higher photocurrent.

D If the intensity of the radiation is increased, the ammeter will register a higher photocurrent.

Changing the wavelength of the radiation changes the KE_{max} of the electrons, it does not change the rate of emission of photoelectrons. Switching the polarity of the p.d. source will not prevent the emission of photoelectrons as long as the radiation is above the threshold frequency. Increase the intensity of radiation will increase the current as the rate of emission of photoelectrons will increase.

3 In a particular photoelectric experiment, it was found that when light of wavelength 187 nm is incident on the metal surface, the stopping potential is 2.70 V.

What will be the stopping potential if light of wavelength 87 nm is used instead?

A 1.70 V **B** 4.94 V **C** 10.3 V **D** No electrons will be emitted

$$h\frac{c}{\lambda} = \phi + eV_S$$

$$\left(6.63\times10^{-34}\right)\frac{\left(3.0\times10^{8}\right)}{\left(187\times10^{-9}\right)} = \phi + \left(1.6\times10^{-19}\right)(2.7)$$

$$\phi = 6.32\times10^{-19}\ \text{J}$$

When wavelength is changed to 87 nm,

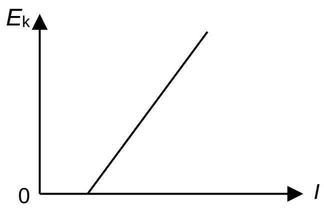
$$\left(6.63\times10^{-34}\right)\frac{\left(3.0\times10^{8}\right)}{\left(87\times10^{-9}\right)} = 6.32\times10^{-19} + \left(1.6\times10^{-19}\right)V_S$$

$$V_S = 10.3\ \text{V}$$

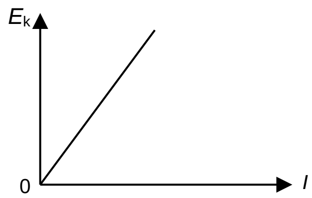
4 In a photoelectric emission experiment using light of a certain frequency, the maximum kinetic energy E_k of the emitted photoelectrons is measured.

Which graph represents the way in which E_k depends on the intensity I of the light?

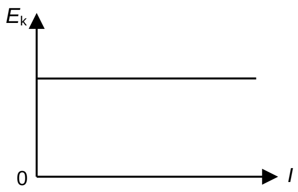
A



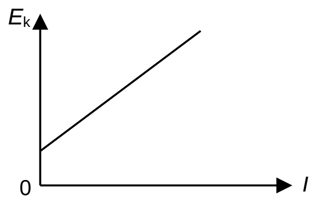
B



C



D



In photoelectric effect, kinetic energy E_k is independent of the intensity I of light.

Line Spectra

5 Which one of the following provides direct evidence for the existence of discrete energy levels in an atom?

A The continuous spectrum of the light emitted by a white-hot metal.

B The emission of photoelectrons from a metal.

C The ionisation of gas atoms when bombarded by alpha particles.

D The line emission spectrum of a gas at low pressure.

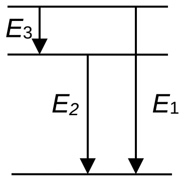
6 Transitions between three energy levels in a particular atom give rise to three spectral lines of wavelengths, in order of increasing magnitude λ_1, λ_2 and λ_3. Which of the following equations correctly relates λ_1, λ_2 and λ_3?

A $\frac{1}{\lambda_1} = \frac{1}{\lambda_2} + \frac{1}{\lambda_3}$

B $\frac{1}{\lambda_1} = \frac{1}{\lambda_3} - \frac{1}{\lambda_2}$

C $\frac{1}{\lambda_1} = \frac{1}{\lambda_2} - \frac{1}{\lambda_3}$

D $\lambda_1 = \lambda_2 + \lambda_3$

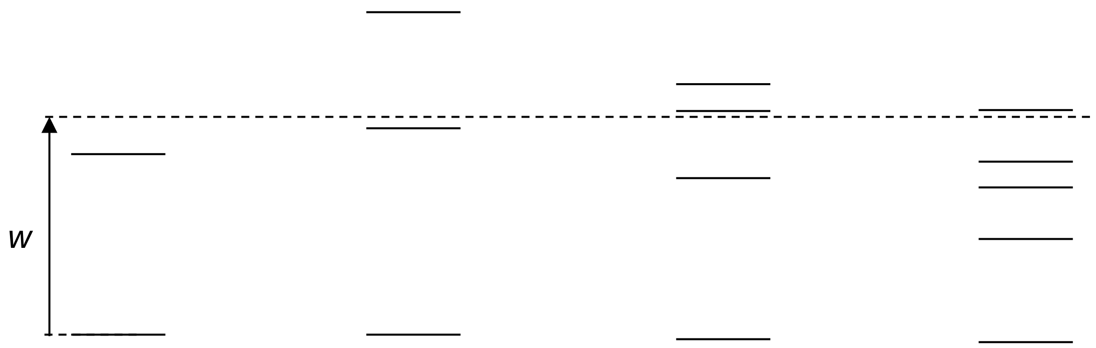


Since $\lambda_1 < \lambda_2 < \lambda_3$

Then $f_1 > f_2 > f_3$ and $E_1 > E_2 > E_3$.

$$E_1 = E_2 + E_3$$
$$\frac{hc}{\lambda_1} = \frac{hc}{\lambda_2} + \frac{hc}{\lambda_3}$$
$$\frac{1}{\lambda_1} = \frac{1}{\lambda_2} + \frac{1}{\lambda_3}$$

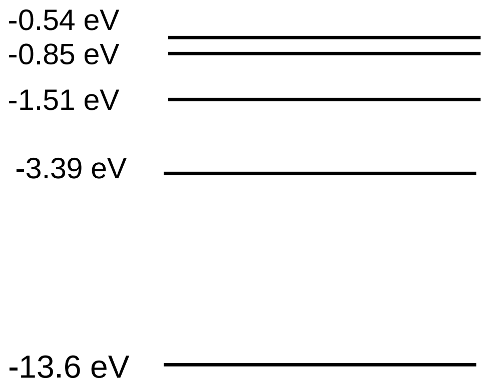
7 The diagram shows the electron energy levels, referred to the ground state (lowest possible energy) as zero, for four different isolated atoms. Which atom can produce radiation of the shortest wavelength when atoms in the ground state are bombarded with electrons of energy W?



A **B** **C** **D**

Shortest wavelength, implies maximum energy difference since E_1-E_2 = hf. Since all ground level energies are the same, the largest energy difference between any 2 levels less then *W* will be B.

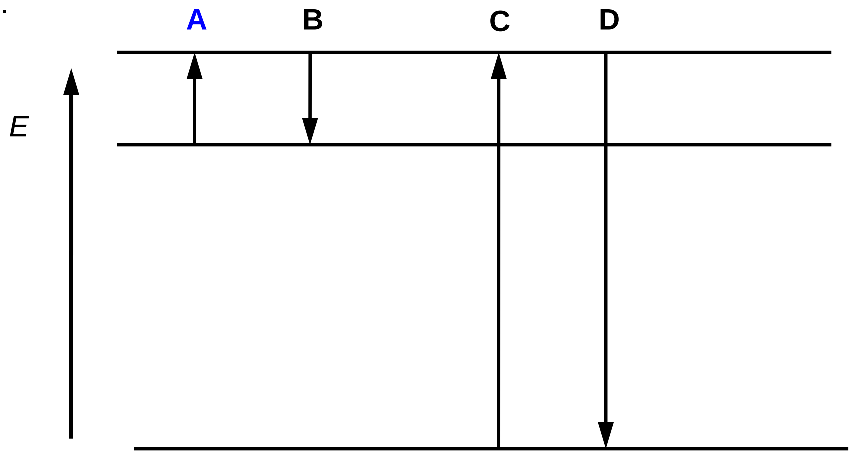
8 Some of the energy levels of the hydrogen atoms are shown.



How many maximum possible spectral emission lines can be observed if photons each of energy 12.85 eV are incident onto the hydrogen atoms that are initial at ground state?

A 0 **B** 3 **C** 6 **D** 10

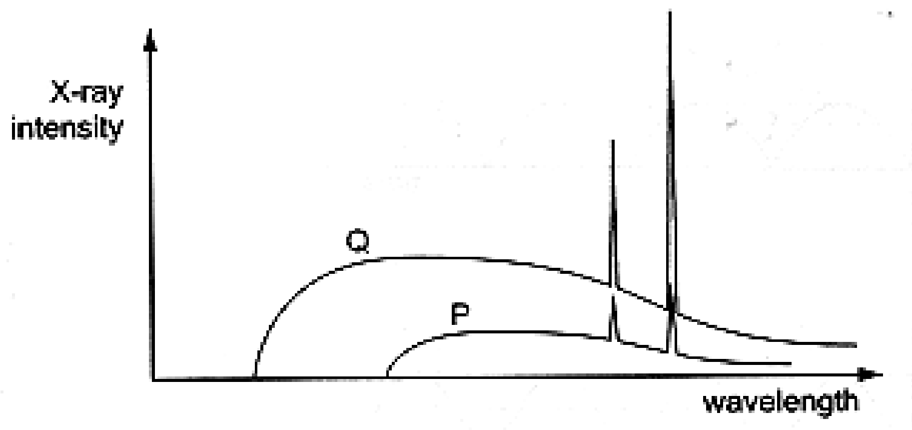
9 The diagram illustrates four transitions between three discrete energy levels of an isolated atom.



Which transition produces the line of longest wavelength in the absorption spectrum of a gas of these atoms?

X-Rays

10 In the figure below, graph P shows an X-ray spectrum from an X-ray tube.



What are the possible changes that can be made to obtain graph Q?

A Change the target metal.

B Increase the filament current of the cathode.

C Reduce the distance between the cathode and the target.

D Increase the potential difference between the cathode and target.

Wave – Particle Duality

11 What is the de Broglie wavelength of a particle of mass, *m* and kinetic energy, *E*?

A $\dfrac{h}{\sqrt{mE}}$ **B** $h\sqrt{2mE}$ **C** $h\sqrt{\dfrac{2}{mE}}$ **D** $\dfrac{h}{\sqrt{2mE}}$

12 A beam of electrons is incident on a crystal lattice. The regularly spaced parallel planes of ions in the lattice can serve as a diffraction grating. The spacing between each plane is 1 x 10^{-8} m. In order for significant diffraction to occur, the kinetic energy of the each electron should be of the order of

A 10^{-2} eV **B** 10^{-21} eV **C** 10^{-26} eV **D** 10^{-34} eV

13 A proton has a kinetic energy of 1.00 MeV. If its momentum is measured with an uncertainty of 1.00 %, what is the minimum uncertainty in its position?

A 1.15×10^{-21} m **C** 1.23×10^{-10} m

B 2.87×10^{-12} m **D** 1.24×10^{8} m

$\Delta p = 0.01\ p$
and $p = (2m\ KE)^{1/2}$ (using $KE = \frac{1}{2} mv^2$ and $p = mv$)

hence $\Delta p\ \Delta x = h$ implies

$$\Delta x = \frac{h}{0.01\times\sqrt{2\times1.67\times10^{-27}\times1.0\times10^{6}\times1.6\times10^{-19}}} = 2.87\times10^{-12} \text{ m}$$

Discussion Questions

Photoelectric Effect

1 Electromagnetic radiation is incident normally on the surface of a metal. Electrons are emitted from the surface and these are attracted to a positively charged electrode, as shown in Fig. 1.1.

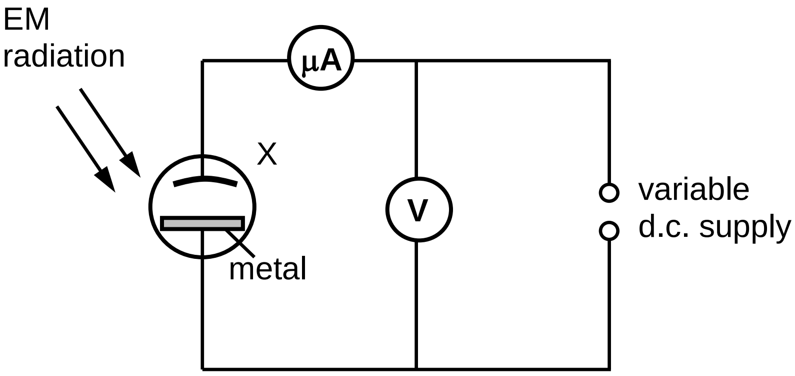


Fig 1.1

(a) Name the effect which gives rise to the emission of the electrons.

The photoelectric effect

(b) State a word equation, based on the principle of conservation of energy, which describes this effect.

The energy of the incident photon is equal to the sum of the work function energy of the metal surface and the maximum kinetic energy of the emitted photoelectrons

(c) **(i)** The current recorded on the microammeter is 2.1 μA. Calculate the number of electrons emitted per second from the surface.

$$I = \frac{Q_{total}}{t} = \frac{N_e e}{t}$$

$$\therefore \frac{N_e}{t} = \frac{I}{e}$$

$$= \frac{2.1 \times 10^{-6}}{1.6 \times 10^{-19}}$$

$$= 1.3 \times 10^{13}$$

(ii) The incident radiation has wavelength 240 nm. Calculate the energy of a photon incident on the surface.

$$E = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34})(3.0 \times 10^{8})}{(240 \times 10^{-9})}$$

$$= 8.3 \times 10^{-19} \text{ J}$$

(d) The intensity of the incident radiation is 8.2 x 10^3 W m^{-2} and the area of the surface is 2.0 cm^2.

(i) Calculate the power of the radiation incident on the surface.

$$P = Intensity \times Area$$
$$= (8.2 \times 10^3)(2.0 \times 10^{-4})$$
$$= 1.6 \text{ W}$$

(ii) Calculate the number of photons incident per second on the surface.

$$P = \frac{E_{total}}{t} = \frac{N_p(E_{1\,photon})}{t}$$
$$\therefore \frac{N_p}{t} = \frac{P}{E_{1\,photon}}$$
$$= \frac{1.6}{8.3 \times 10^{-19}}$$
$$= 1.9 \times 10^{18}$$

(iii) Hence determine the ratio

$$\frac{\text{number of electrons emitted per second}}{\text{number of photons incident per second}}$$

$$ratio = \frac{1.3 \times 10^{13}}{1.9 \times 10^{18}} = 6.8 \times 10^{-6}$$

(e) If the intensity of the radiation is doubled, state and explain the effect on

(i) the saturated current,

Doubled

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(ii) the maximum kinetic energy of the photoelectrons.

No change.

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Line Spectra

2 **(a)** Explain how the line spectrum of hydrogen provides evidence for the existence of discrete electron energy levels in atoms.

As each line on the line spectrum corresponds to photons of a single wavelength, and hence a single frequency, this implies that the energies of the photons emitted are discrete. This is only possible if the energy levels of electrons within the atom are discrete as well.

(b) Some of the electron energy levels in atomic hydrogen are illustrated in Fig. 2.1.

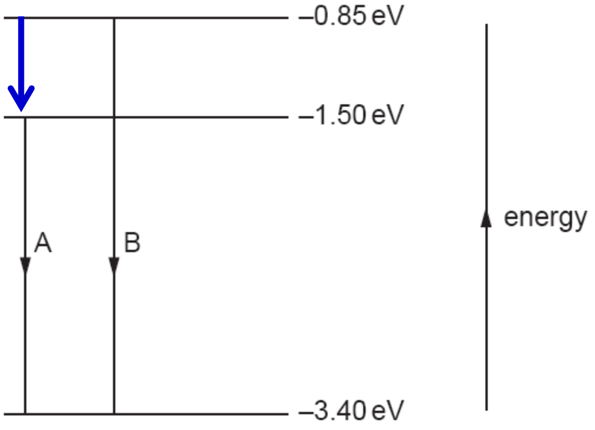


Fig. 2.1

Two possible electron transitions A and B giving rise to an emission spectrum are shown.

These electron transitions cause light of wavelengths 654 nm and 488 nm to be emitted.

(i) On Fig. 2.1, draw an arrow to show a third possible transition.

(ii) Calculate the wavelength of the emitted light for the transition in **(i)**.

$$E_3 - E_2 = \frac{hc}{\lambda}$$

$$\therefore \lambda = \frac{(6.63 \times 10^{-34})(3.0 \times 10^{8})}{(1.50 - 0.85)(1.6 \times 10^{-19})}$$

$$= 1910 \text{ nm}$$

3 The diagram below illustrates some of the electron energy levels in an isolated atom of lithium.

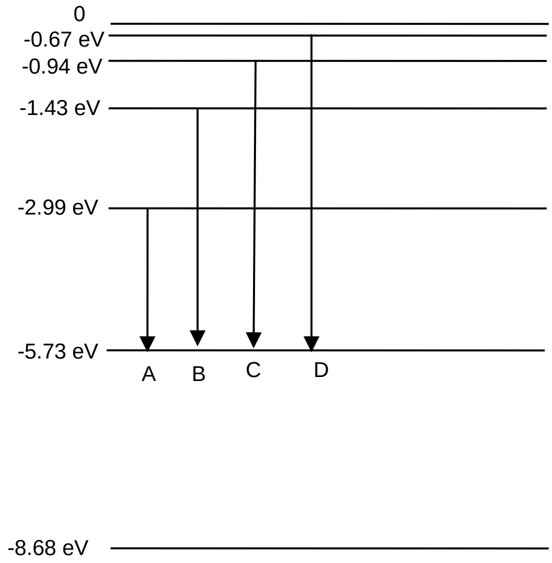


Fig. 3.1

(a) The outer electron of a lithium atom is found in the lowest energy level shown. Determine the amount of energy required to remove this electron from the atom and express your answers in Joules.

Energy required = $8.68 \times (1.6 \times 10^{-19}) = 1.39 \times 10^{-19}$ J

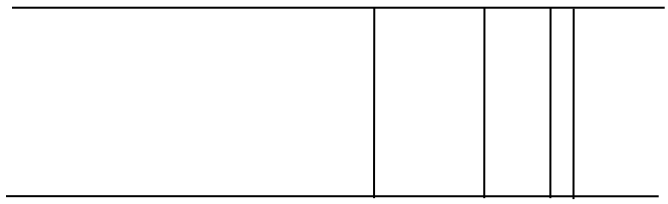
(b) **(i)** State the transition A, B, C, D that would lead to emission of radiation of the shortest wavelength.

Transition D

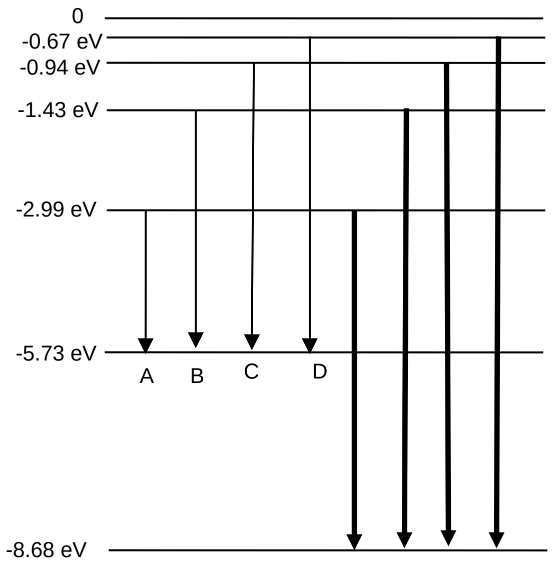
(ii) Calculate the wavelength of this radiation and state the region of the electromagnetic spectrum in which this radiation lies.

$\lambda = \dfrac{hc}{\Delta E} = \dfrac{(6.63 \times 10^{-34}) \times (3.0 \times 10^{8})}{(-0.67 - (-5.73)) \times (1.6 \times 10^{-19})} = 2.45 \times 10^{-7}$ m ; Ultraviolet region

(iii) Sketch the appearance of the spectrum which these four transitions produce.



(b) On Fig. 3.1, draw four transitions of greater energy change which give rise to another set of wavelengths.



4 **(a)** Explain what is meant by an *energy level* of an electron in an atom.

It is the quantized energy corresponding to an allowed state (or orbital) of the electron within the atom.

(b) Fig. 4.1 shows a cooler region of hydrogen gas surrounding a hot gas cloud emitting white light.

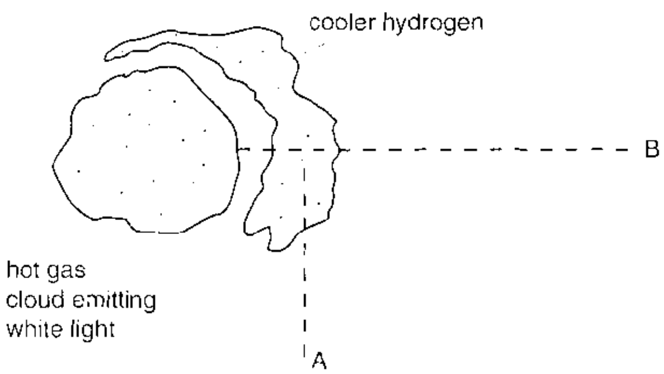


Fig. 4.1

(i) State and explain the type of hydrogen spectrum observed from

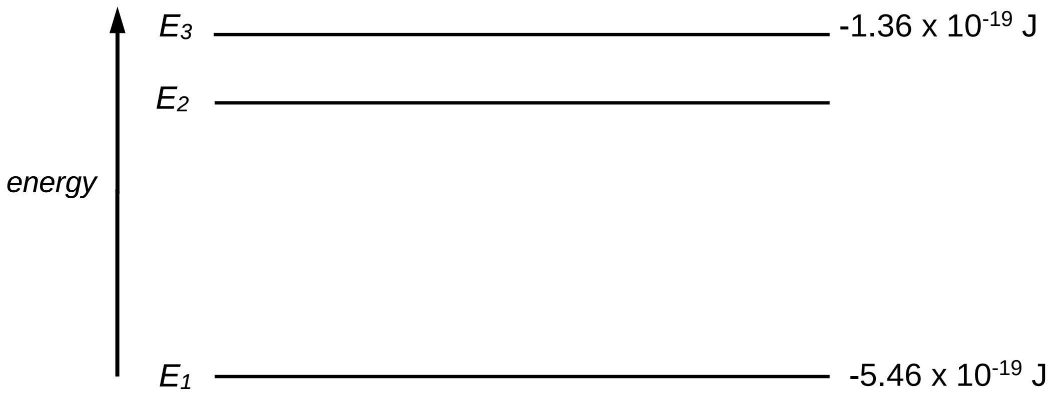
1. point A

An emission spectrum, which consists of coloured lines on a dark background, is observed. When the excited atoms of the cooler hydrogen de-excites, it emits photons having only the energies that correspond to the energy difference between 2 discrete energy levels of the hydrogen atoms.

2. point B

An absorption spectrum, which consists of dark lines on a coloured background, is observed. This is due to absorption of photons having the energies that correspond to the energy difference between 2 discrete energy levels when the electrons of the cooler hydrogen atoms are being excited. Thus light of these frequencies appear to be missing from the continuous spectrum from the white light emitted from the hot gas cloud

(ii) Fig. 4.2 shows some of the energy levels of a hydrogen atom



(not to scale)

Fig. 4.2

1. Use the values of the energy levels E_3 and E_1 shown in Fig. 4.2 to calculate the frequency of the electromagnetic radiation emitted when an electron makes a transition between energy levels E_3 and E_1.

$$E_3 - E_1 = hf$$

$$\therefore f = \frac{(5.46 - 1.36) \times 10^{-19}}{(6.63 \times 10^{-34})}$$

$$= 6.18 \times 10^{14} \text{ Hz}$$

2. The frequency of radiation emitted when an electron makes a transition between energy levels E_3 to E_2 is 1.60 X 10^{14} Hz. Determine the wavelength of the electromagnetic radiation when an electron makes a transition between energy levels E_2 and E_1.

$$E_{3to1} = E_{3to2} + E_{2to1}$$

$$hf_{3to1} = hf_{3to2} + hf_{2to1}$$

$$f_{2to1} = f_{3to1} - f_{3to2}$$

$$\frac{C}{\lambda_{2to1}} = (6.18 - 1.60) \times 10^{14}$$

$$\lambda_{2to1} = \frac{3.0 \times 10^8}{(6.18 - 1.60) \times 10^{14}}$$

$$= 655 \text{ nm}$$

X-Rays

5 Fig. 5.1 shows the main structure of an X-ray tube and Fig. 5.2, the spectrum of the X- rays emitted from such a tube.

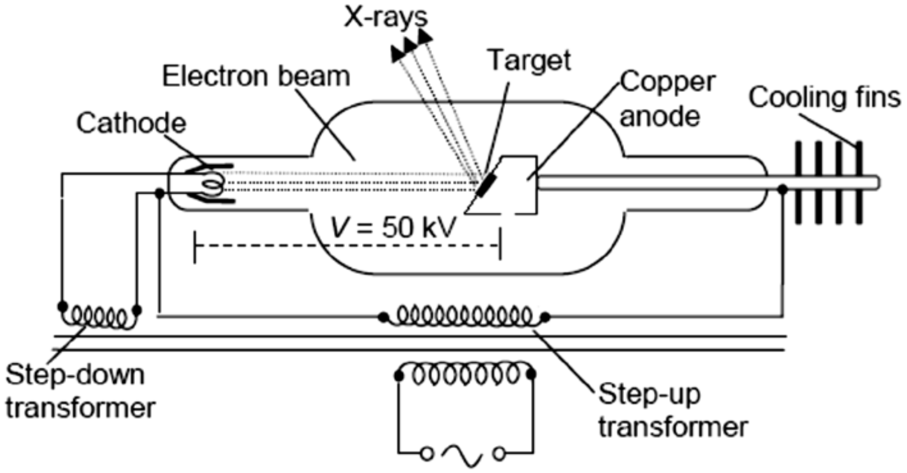


Fig. 5.1

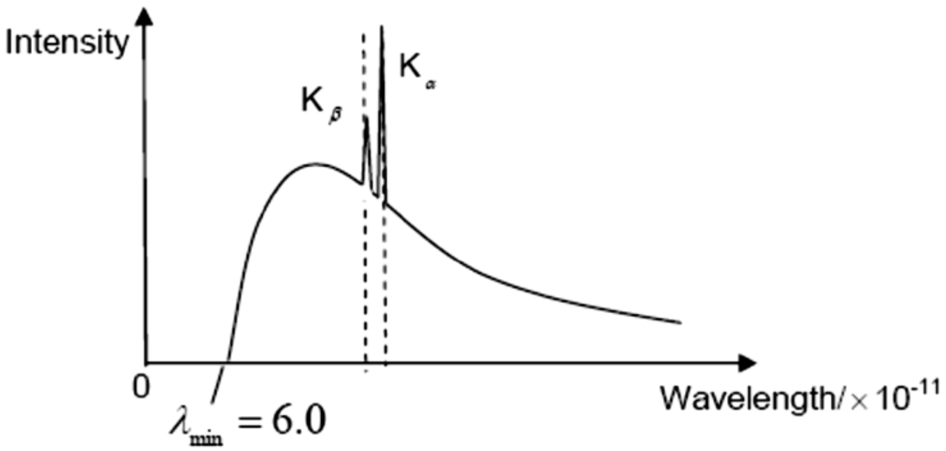


Fig. 5.2

(a) Suggest two important properties of the materials used for the cathode and target of such a tube.

The cathode should have

1. A low value for its work function so that electrons can escape from its surface easily.
2. A low heat capacity so that less heat is required to raise its temperature.

The target should have

1. A high melting point to withstand the large amounts of heat produced when electrons bombard it.
2. Has high atomic number so that it is more efficient in the production of X-rays,
3. A good conductor of heat so that heat can be removed from it easily.

(b) Explain the production of an X-ray spectrum which contains both a continuous spectrum and a characteristic line spectrum.

The characteristic line spectrum are produced when the fast bombarding electrons knocks out inner shell electrons from the target atoms and the vacant shells are subsequently refilled by electrons from the outer shells. This result in the emission of X-ray photons with energies that correspond to the energy differences between the energy levels of the two shells, hence producing X-rays of specific frequencies.

X-rays are also produced when the fast bombarding electrons are accelerated as it strikes the target. This process is called bremsstrahlung (German for "braking radiation"). As different amounts of their kinetic energies are lost, X-ray photons of various wavelengths are emitted, resulting in the continuous spectrum being produced.

(c) Determine the potential difference between the target and cathode when this spectrum was produced.

$$eV = \frac{hc}{\lambda_{min}}$$

$$V = \frac{hc}{e\lambda_{min}}$$

$$= \frac{(6.63 \times 10^{-34})(3.0 \times 10^{8})}{(1.6 \times 10^{-19})(6.0 \times 10^{-11})}$$

$$= 21 \text{ kV}$$

(d) The X-ray tube operates at an electron beam current of 0.5 A and only 0.2 % of the total energy of the high-speed electrons is converted to X-rays. Explain why cooling of the target is necessary.

Assuming energy not converted to X-rays is loss as heat, the power loss as heat when the tube is in operation $= 0.998\,(0.5)(21 \times 10^3) = 10$ kW. Thus if the target is not cooled, heat will build up rapidly within the target which will in turn cause its temperature to increase to its melting point.

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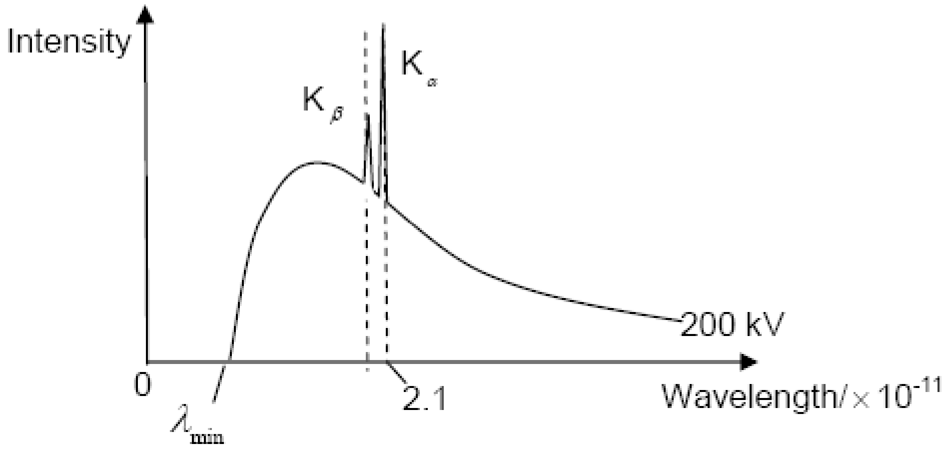
6 The X-ray spectrum produced by an X-ray tube with tungsten anode and maintained at a constant accelerating potential of 200 kV is as shown below.



(a) Explain the following features of the graph:

(i) the existence of a minimum wavelength, λ_{min},

The minimum wavelength λ_{min} is produced when the energy of the accelerated electron from the cathode, eV is completely converted into a photon of X-ray.

$$\lambda_{min} = \frac{hc}{eV}$$

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(ii) the wavelength of the K_β - line is shorter than the wavelength of the K_α - line,

A photon of the K_α line is produced when an electron from the L-shell transits to the K-shell.
A photon of the K_β line is produced when an electron from the M-shell transits to the K-shell.
The energy difference ($E_L - E_K$) of the electron from the L-shell to the K-shell is less than ($E_M - E_K$), the energy difference of the electron from the M-shell to the K-shell.

From the equation, $\frac{hc}{\lambda_\alpha} = (E_L - E_K)$ and $\frac{hc}{\lambda_\beta} = (E_M - E_K)$

Since $(E_M - E_K) > (E_L - E_K)$, $\lambda_\beta < \lambda_\alpha$.

(iii) the intensity of the K_α - line is relatively higher than that of the K_β - line.

Intensity of the K_α line is relatively higher than that of the K_β line because the rate of emission of K_α photons is greater than the rate of emission of K_β photons. This is because the electrons in the L-shell are closer to the K-shell, hence there is a greater probability that the vacancy in the K-shell is filled by an electron from the L-shell than from the M-shell.

(c) Calculate the minimum accelerating potential required to produce the X-ray photons that has the same wavelength as the K_α – line.

Wavelength of the K_α line, $\lambda_\alpha = 2.1 \times 10^{-11}$ m

$$eV_{\text{min}} = \frac{hc}{\lambda_\alpha}$$

$$V_{\text{min}} = \frac{(6.63 \times 10^{-34})(3.0 \times 10^{8})}{(2.1 \times 10^{-11})(1.6 \times 10^{-19})} = 59 \text{ kV}$$

(d) Describe and explain changes to the graph, if any, when the following modifications are made, with other factors remaining unchanged:

(i) the temperature of the cathode is increased by increasing the current in the cathode,

When the temperature of the cathode is increased,
- the rate of emission of electrons from the cathode increases.
- the rate of collision of electrons with the target increases.
- the rate of emission of X-ray photons increases.
- the intensity of the X-rays increases for all wavelengths, but the minimum wavelength, λ_{min} and the wavelengths of the characteristic X-rays remain unchanged.

(ii) the accelerating potential is increased to 250 kV,

When the accelerating potential is increased to 250 kV,

- the minimum wavelength $\lambda_{min} = \dfrac{hc}{eV}$, decreases because *V* increases.
- the intensity of all wavelengths increases because the speed of the electrons increases.
- the rate of collision of electrons with the target increases.
- more X-rays photons produced per second.
- the wavelengths of the characteristic X-rays remain unchanged.

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(iii) the accelerating potential is reduced to 50 kV.

When the accelerating potential is reduced to 50 kV < 59 kV, i.e., less than the minimum potential required (from (b) above), the characteristic X-rays will not be generated, since 50 kV accelerating voltage is not even enough to excite the n=1 shell electron to the n=2 shell (since 59 kV is required), thus it is definitely impossible to ionize the n=1 shell electron. Hence, the characteristic wavelength will not be produced. The minimum wavelength $\lambda_{min} = \dfrac{hc}{eV}$, however increases because *V* decreases.

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Wave – Particle Duality

7 A parallel beam of violet light of wavelength 4.5 x 10^{-7} m and intensity of 700 W m^{-2} is incident normally on a surface.

(a) Calculate the energy of a photon of violet light.

$$E = hf$$

$$E = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{4.5\times10^{-7}}$$ = 4.4 x 10^{-19} J

(b) Calculate the number of photons per second incident on 1.0 x 10^{-4} m^{-2}.

$$I = \frac{N}{tA}hf = \frac{NE}{tA}$$

$$\frac{N}{t} = \frac{IA}{E} = \frac{700\times1.0\times10^{-4}}{4.4\times10^{-19}}$$

= 1.58 x 10^{17} s^{-1}

(c) State the de Broglie relation for the momentum *p* of a particle in terms of its associated wavelength λ.

$$\lambda = \frac{h}{p}$$

(d) Calculate the momentum of a photon of violet light.

$$p = \frac{h}{\lambda}$$

$$p = \frac{6.63\times10^{-34}}{4.5\times10^{-7}} = 1.47\times10^{-27}\text{ Ns}$$

(e) Calculate the change in momentum of the photons incident on 1.0 x 10^{-4} m^{-2} of the surface in 1 second. Assume that the photons are absorbed by the surface.

Since photons are absorbed by the surface, final momentum = 0 Ns

Change in momentum of a photon of the violet light

= $|p_f - p_i|$

= 0 – (-1.47 $\times10^{-27}$) = 1.47 $\times10^{-27}$ Ns

Total change in momentum in one second = 1.47 $\times10^{-27}$ x 1.58 x 10^{17}

= 2.32$\times10^{-10}$ Ns

(f) Suggest why the quantity you have calculated in **(e)** is referred to as 'radiation pressure'.

By Newton's 2nd Law, the force on the photons is proportional to the rate of change of momentum of the photons. By Newton's 3rd law, the photons exerts an equal and opposite force on the surface. Hence when photons are incident on a surface, they exert a force on the surface.

The force of photons on the surface is numerically equal to the rate of change of momentum of the photons in c(i).

And since p = F/A and c(i) gives Force exerted on 1 x 10^{-4} m^2, the quantity in c(i) can be referred to as 'radiation pressure'.

8 Fig. 8.1 shows part of the apparatus for an experiment in which electrons travel through a thin layer of graphite(carbon atoms) and emerge to concentric rings on a fluorescent screen.

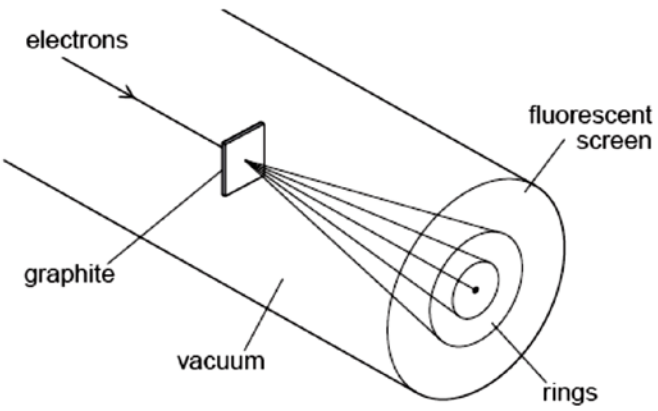

Fig. 8.1

(a) Use the ideas of de Broglie to explain how this experiment demonstrates the wave-nature of electrons.

The ring patterns observed in the experiment showed the diffraction, a behavior associated with waves, of the electron beam. This is in line with the wave-particle duality proposed by de Broglie suggests that particles at times will exhibit wave behavior.

(b) Calculate the de Broglie wavelength of an electron travelling with speed 2.8 x 10^7 m s^{-1}.

$$\lambda = \frac{h}{mv}$$

$$= \frac{(6.63 \times 10^{-34})}{(9.11 \times 10^{-31})(2.8 \times 10^{7})}$$

$$= 2.60 \times 10^{-11}\ m$$

(c) The speed of the electrons is gradually increased.

State and explain what change, if any, is observed in the pattern on the screen.
The momentum of the electrons increases as its speed is increased. Thus its associated de Broglie's wavelength decreases. This will in turn cause the angle of diffraction to decrease and the rings to decrease in diameter.

9 A beam of electrons is directed along a normal towards a barrier, as shown in Fig. 9.1.

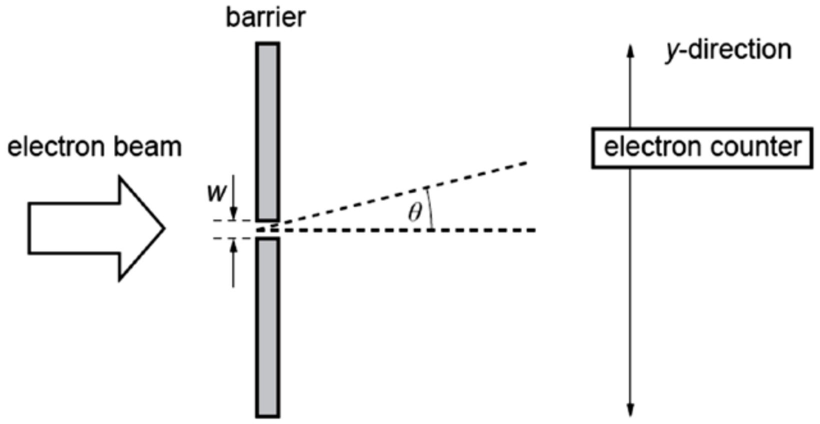

Fig. 9.1

The barrier contains a single slit of width w. Beyond the slit there is a detector that counts electrons. This can be moved in the y-direction to compare the rate of arrival of electrons at different values of the angle θ from the original direction of the beam.

(a) **(i)** Louis de Broglie suggested that some aspects of the behavior of electrons can be explained using a wave model. Describe the main features of de Broglie's model of the electron.

de Broglie's model of the electron is one in which exhibits both particle behavior (i.e. collisions) and wave behavior (i.e. diffraction). The electron can thus be described both by its momentum p, a quantity associated with particles, as well as its wavelength λ, a quantity associated with waves and λ is related to p by $\lambda = \frac{h}{p}$.

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(ii) Use the wave model to explain how the electron beam spreads out beyond the slit.

When electrons with wavelengths that are in the order of magnitude as the slit width, diffraction occurs and the electron beam will bend towards the barrier.

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(b) State and explain one aspect of this experiment that cannot be explained using the wave model.

An interference pattern is observed with maximas which are positions where more electrons strike) and minimas which are positions where little electrons strike. The wave model is unable to explain how single electrons contribute individually to the formation of the interference pattern as it means that the wave characteristic of each electron will have to interfere with itself.

(c) Werner Heisenberg used a different approach involving what is now known as the uncertainty principle. This can also be used to explain why the electron beam spreads out after passing through the slit. One version of this involves the equation

$$\Delta y \Delta p \geq h$$

Explain how the terms below apply to electrons as they pass through the slit.

(i) Δy

is the uncertainty in the vertical position of the election as it passes through the slit (the slit width can be taken to be Δy).

(ii) Δp

is the uncertainty of the vertical component of momentum as the electron passes through the slit.

(d) Hence use the uncertainty principle to explain why

(i) the beam spreads out,

As the electrons pass through the slit, there will be an uncertainty in its vertical component of its momentum. Thus the vertical component of its momentum, and hence its velocity, may not necessarily be zero after passing through the slit.

(ii) the beam is spread out more when the slit is narrower (smaller w),

When the slit is narrower, the uncertainty in its vertical position as it passes through the slit is smaller. Hence by the Heisenberg Uncertainty Principle, the uncertainty in its vertical component of momentum increases, which in turn implies that the path of the electron will deviate more.

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(iii) the beam is spread out less when the incoming electrons have greater linear momentum.

For the same slit width, the limit to the uncertainty in its vertical component remains the same. Hence with a larger momentum in the horizontal direction, the resultant momentum of the electrons after passing the slit will have a smaller angle of deviation, thus the beams spreads out less.

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<u>Answer Key</u>

Self-Attempt Questions

1 D **2** D **3** C **4** C **5** D **6** A **7** B **8** A **9** A **10** D **11** D **12** A **13** B

Discussion Questions

1 (c)(i) 1.3×10^{13} **(ii)** 8.3×10^{-19}J **(d)(i)** 1.6 W **(ii)** 1.9×10^{18} **(iii)** 6.8×10^{-6} **2 (b)(ii)** 1910 nm **3 (a)** 1.39×10^{-19} J **(b)(ii)** 245 nm **4 (b)(ii)1.** 6.18×10^{14} Hz **2.** 655nm **5 (c)** 21 kV **6 (c)** 59 kV **7 (a)** 4.42×10^{-19} J **(b)** 1.58×10^{17} s^{-1} **(d)** 1.47×10^{-27} Ns **(e)** 2.32×10^{-10} Ns **8 (b)** 2.60×10^{-11} m